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ANALYTICAL HEAT TRANSFER INVESTIGATION OF INSULATED LIQUID METHANE FUSELAGE TANKS FOR SUPERSONIC CRUISE AIRCRAFT

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16. Abstract

Liquid methane boiloff from fuselage tanks was computed for typical SST missions for cruise Mach numbers of 2.7 and 3.5, insulation thicknesses of 0.5, 1.0, and 2.0 in. (1.27, 2.54, and 5.08 cm), various vent pressure settings, and saturated and subcooled fuel. Boiloff rates during fuel fill and ground hold are discussed. Boiloff losses less than 2.5 percent are possible for a cruise Mach number of 2.7 and an insulation thickness of 1.0 in. (2.54 cm).

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SUMMARY

An analytical investigation was conducted to evaluate the insulation requirements for liquid methane tanks located in the fuselage of supersonic-transport-type aircraft flying at cruise Mach numbers of 2.7 and 3.5. The results are compared with those from a previous investigation of the insulation requirements for wing tanks in the same aircraft. The boiloff losses as a percentage of the initial fuel stored in the tanks is somewhat higher for fuselage tanks than for wing tanks with the same insulation thickness because the fuel has to be stored for a longer period of time if fuel is first used from the wing tanks. The total boiloff loss from the fuselage tanks can be less than 2.5 percent of the initial fuel weight in the tanks with 1.0 inch (2.54 cm) of insulation for a cruise Mach number of 2.7. Increasing the cruise Mach number to 3.5 increases the boiloff loss to only 3.1 percent of the initial fuel stored. Similar boiloff losses are obtained with fuel initially subcooled slightly more than 20° F (11 K) and stored in tanks that vent at 4 psi (2.8 N/cm^2) above ambient and with initially saturated fuel at 1 atmosphere and stored in tanks that vent at an absolute pressure of 15 psia (10.3 N/cm^2 abs). The amount of subcooling has a very significant effect on boiloff losses. Reducing the initial subcooling from 25° to 20° F (14 to 11 K) approximately doubles the boiloff from the fuselage tanks.

The optimum insulation thickness to give minimum total weight penalty for boiloff plus insulation weight is twice as thick for fuselage tanks as for wing tanks (2.0 in. against 1.0 in. or 5.08 cm against 2.54 cm). It was found that boiloff losses from fuselage tanks could be eliminated for insulation thicknesses as low as 0.5 inch (1.27 cm) using initially saturated fuel and having tanks that withstand an internal pressure of 30 psia (20.7 N/cm^2 abs).

INTRODUCTION

This report presents a performance analysis of cryogenic fuel fuselage tanks that could be used in liquid methane fueled, supersonic cruise aircraft such as a commercial supersonic transport (SST). Fuel boiloff and insulation weight are compared for several insulation thicknesses, two different initial fuel conditions, and two SST missions.

The potential benefits of using liquid methane as a fuel for supersonic aircraft have been discussed in a number of reports such as references 1 to 5. References 6 and 7 discussed some of the possible structural approaches to tank design for aircraft using liquid methane fuel. Reference 8 presented results of an analysis showing the effect various insulation and fuel storage systems for wing tanks of an SST have on fuel boiloff and system temperature histories. Although wing tanks suffer the problems of less advantageous surface to volume ratios than fuselage tanks and aerodynamic heating occurs on both the top and bottom surfaces for wing tanks, the fuel will generally be used from the wing tanks in the early part of the mission so that aerodynamic heating occurs for only a relatively short time. At least some of the fuselage tanks will contain fuel for the entire mission. In addition a larger portion of the fuselage tank wall (neglecting the end walls) in contact with liquid methane is subjected to aerodynamic heating than for wing tanks. As a result, fuselage tanks insulation problems are as important as those for wing tanks. This report on the effect of several insulation thicknesses and fuel storage methods for liquid methane in fuselage tanks is a continuation of the investigation reported in reference 8 on wing tanks using the same assumed missions and other general assumptions.

The data were generated by a computer code as presented in reference 8 which simulates the heat transfer effects of an SST mission on an insulated fuselage tank system. The simulation includes fuel fill, ground hold, and fuel usage during takeoff and climb, supersonic cruise, descent, and landing. The insulation properties used represent goals of current NASA-sponsored research. Insulation thicknesses from 0.5 to 2.0 inches (1.27 to 5.08 cm) at a specific weight of 2 pounds per cubic foot (32 kg/m^3) were considered. With saturated liquid methane in the tanks, vent pressure seetings of 15 and 30 psia (10.3 and 20.7 N/cm^2 abs) were considered; for initially subcooled liquid methane (25° and 20° F (14 and 11 K) subcooling), the vent pressure setting during the mission was 4 psi (2.8 N/cm^2) above ambient. Missions at cruise Mach numbers of 2.7 and 3.5 and a range of 3476 nautical miles (6400 km) were considered.

SYMBOLS

M	Mach number
P	pressure, psi; N/cm^2
Q	heat added, Btu; W-hr
T	temperature, ^{o}F; K
t	thickness, in.; cm
W	weight of fluid, lb; kg
$\dot{W}$	fuel fill rate, lb/min; kg/min
θ	time, min

Subcripts:

bo	boiloff
c	cabin
evap	total fuel evaporated across interface
f	total weight of fuel in fuselage or wing tanks
g	gas
I	insulation
l	liquid
ref	reference
s	local
used	total fuel used

METHOD OF ANALYSIS

The METHOD OF ANALYSIS section of reference 8 defines the SST missions, the fuel weight conversion (conversion of JP fueled SST airplane to methane fueled SST), the heat transfer modes and the fluid thermodynamics which were the basis for the computer simulations. The fuselage tanks contain about one-half of the total liquid methane fuel required including reserves. The two SST missions (flight plans) used for simulation purposes were obtained from reference 8 and are shown in figure 1. Over a 3476-nautical-mile (6400-km) range, the Mach 2.7 SST flies at cruise altitudes of 60 000 to 70 000 feet (18 300 to 21 300 m) and the Mach 3.5 SST flies at cruise altitudes of

65 000 to 74 000 feet (19 700 to 22 500 m). Figure 1 also shows the fuel usage pattern for Mach 2.7 and 3.5 cruise flights (without boiloff losses) consists of consuming all the fuel in the wing tanks in the first 74 and 65 minutes of the mission, respectively. The fuel would then be used from the fuselage tanks to complete the mission.

The mission simulation consists of subjecting the fuselage tanks to the heat transfer environment of the following series of events; fuel fill and ground hold, takeoff, climb, cruise (at Mach 2.7 or 3.5), descent and landing. Data computed during the simulation include (1) a temperature history of the tank structure, (2) heat transfer coefficient and heat fluxes at the boundaries, (3) average temperatures and pressues of liquid and gaseous methane and liquid methane level in the tanks as fuel is used, and (4) methane evaporation across the liquid-gaseous interface and weight of boiloff methane vented overboard.

Tank Models

A fuselage storage void space obtained from reference 7 determined the fuselage tank configuration. Two parts make up the model: (1) a portion of the tank symmetric about a vertical plane coincident with the longitudinal axis of the fuselage, and (2) the tank ends. Figure 2 shows the heat transfer models used. The thin metallic tanks walls (0.01 to 0.03 in. or 0.025 to 0.076 cm) were removed from the analytical model. However, during fuel fill and ground hold, the boiloff calculations were corrected to include the heat sink effect of cooling 0.03-inch (0.076-cm) metallic tank walls. The percent boiloff required to cool the tank walls from ambient temperature of 70° F (294 K) to liquid methane temperature of -260° F (111 K) is 0.46 percent of the total fuel weight in the filled tanks. This boiloff occurs during the initial minutes of filling and does not result in fuel loss during the flight mission.

Tank Design

The tank cross section is a segment of an 82.25-inch-(208-cm-) radius fuselage section with a height of 45.25 inches (115 cm). The accumulated length of all the fuselage tanks with the above cross section is 142 feet (43.3 m). The fuselage tanks contained about one-half of the total amount of fuel and reserves needed by a fixed wing SST of 500 000 pounds (230 000 kg) gross weight that flies a 3476-nautical-mile (6400-km) mission. A 4 percent ullage space was assumed. Since these tanks fit between fuselage bulkheads 5 feet (1.52 m) apart, 29 tanks are required. Fuel was used from all the tanks simultaneously.

Tank ends are included in the model because their area amounts to 46 percent of the total tank surface area in contact with the liquid fuel when the tanks are full. The ends are exposed to heating by the fuselage bulkheads which are heated by conduction from the aerodynamically heated fuselage skin.

The same materials proposed in reference 8 were used to construct the fuselage tank system. Material properties were also the same as listed in figure 3 of reference 8. An insulation specific weight of 2 pounds per cubic foot (32 kg/m^3) was used for all the calculations and the titanium alloy 6A1-4V was used in all the supporting structure. Three insulation thicknesses were considered on the portion of the tank most directly exposed to aerodynamic heating; 0.5, 1.0, and 2.0 inches (1.27, 2.54, and 5.08 cm). A constant insulation thickness of 0.5 inch (1.27 cm) was used on the tank ends since this surface is exposed to much lower heat fluxes and preliminary calculations indicated negligible reductions in boiloff with thicker (1.0 in. or 2.54 cm) insulation. Insulation thickness for the top of the tank which faces the passenger cabin floor was the same as the aerodynamically heated portion of the tank. The boundary temperature above this insulation was assumed to be 70° F (294 K). A heat source, such as circulating warm air for cabin heating, would be required to maintain this temperature boundary.

RESULTS AND DISCUSSION

Tank Fill and Ground Hold

Fueling an SST with a cryogenic fuel in a reasonably short time period causes boiloff because the wall temperatures are initially much higher than the boiling temperature of the cryogenic fuel. Figure 3 shows the results of calculations of boiloff rates during the fuel fill and ground hold time. The fueling fill rate fraction $\dot{W}/W_f$ was assumed to be 0.05 minute^{-1} ((lb per min)/lb, (kg per min)/kg) which would result in a full tank in about 24 minutes. Figure 3 shows the boiloff rate fractions for fuselage tanks and wing tanks. The wing tank data were obtained from figure 5(a) of reference 8. The wing and fuselage tank data were corrected to include the effects of cooling the tank walls which consisted of converting the heat sink associated with 0.03-inch (0.076-cm) metallic walls that were removed from the tank models into liquid methane boiloff. The additional boiloff was added to the boiloff as calculated during fuel fill and ground hold. Insulation thickness and specific weight and initial fuel condition are the same for both tank systems.

For the fuselage tanks, figure 3 shows a maximum boiloff rate at the beginning of fill at a rate of about 0.0021 minute^{-1} which is one twenty-fifth of the fill rate. For the wing tanks the maximum corrected boiloff rate is 0.0078 minute^{-1} as compared to the 0.0014 minute^{-1} reported in reference 8. This is an increase of initial boiloff rate from one thirty-fifth to one-seventh of the fill rate. The average boiloff rate during the fuel fill time is about 0.0004 minute^{-1} for the wing tanks. Both values are less than one-seventieth of the fill rate.

The boiloff fraction to cool down the tank walls to fuel temperature is 0.0115 for the wing tanks and 0.0046 for the fuselage tanks. The total boiloff fraction for fill and ground hold is lower for the fuselage tanks because of a more favorable tank volume to wetted area ratio.

SST Mission Boiloff

Insulation thickness, tank vent pressure, and initial fuel state effects. - The ratio of boiloff weight to initial total weight of fuel in the tanks as a function of mission time is shown in figure 4. Supersonic cruise at Mach 2.7 begins 25 minutes after takeoff, and fuel usage from the fuselage tanks begins 74 minutes after takeoff which is after the wing tanks have emptied. For saturated methane initially at 1-atmosphere vapor pressure, the boiloff was calculated in this report for tank vent pressure settings of 15 and 30 psia (10.3 and 20.7 N/cm^2 abs), and, therefore, was mainly due to the effects of aerodynamic heating. For subcooled methane at 20° and 25° F (11 and 14 K) of subcooling which corresponds to initial vapor pressures of 4.85 and 4.0 psia (3.35 and 2.8 N/cm^2 abs) (which are near the atmospheric pressures at cruise altitudes) the boiloff was calculated for tank vent pressure settings of 4 psi (2.8 N/cm^2) above ambient.

Figure 4(a) shows boiloff losses for a vent pressure setting of 15 psia (10.3 N/cm^2 abs) and insulation thicknesses of 0.5, 1.0, and 2.0 inches (1.27, 2.54, and 5.08 cm). The total losses from fuselage tanks are 4.2, 2.4, and 1.3 percent of the initial fuel weight contained in the tanks for insulation thicknesses of 0.5, 1.0, and 2.0 inches (1.27, 2.54, and 5.08 cm), respectively. The losses at a vent pressure of 30 psia (20.7 N/cm^2 abs) were also calculated and found to be negligible for an insulation thickness of 0.5 inch (1.27 cm) or greater. This observation complements the work done in reference 8 on wing tanks which results in the possibility of very small venting losses if all the fuel tanks are designed with sufficient strength to allow the pressure in both tank systems to increase from the loading pressure of 1 atmosphere to at least 30 psia (20.7 N/cm^2 abs). Aerodynamic heating is absorbed by the fuel increasing its temperature during the pressure rise from -260° to -242° F (111 to 121 K). Regardless of how the main fuel tank system is designed, the reserve tanks could be designed for no boiloff venting during the mission for adequate reserve fuel purposes. This analysis indicates a 30-psia (20.7-N/cm^2 abs) saturated methane passive system as meeting the above (no boiloff venting) requirements. After a completed mission, the reserve fuel would be allowed to boildown to 1-atmosphere vapor pressure and the resulting boiloff collected by ground equipment for reuse.

Figure 4(b) shows boiloff results of three tanks all with 1.0 inch (2.54 cm) of insulation. One tank which vents at 15 psia (10.3 N/cm^2 abs) contains saturated liquid methane initially at 1-atmosphere vapor pressure. The other two tanks which vent at 4 psi (2.8 N/cm^2) above ambient contain fuel initially subcooled to 20° and 25° F (11 to 14 K) subcooling at 4.85- and 4.0-psia (3.3- and 2.8-N/cm^2 abs) vapor pressure, respectively. The amount of initial fuel subcooling affects the boiloff result comparisons significantly. With 25° F (14 K) of subcooling the initial fuel temperature is about 4° F (2 K) colder than it will be at its saturation temperature at cruise altitude (0.7-psia or 0.5-N/cm^2 abs ambient pressure); while for the tank containing saturated fuel, the initial fuel temperature at 14.7 psia (10.1 N/cm^2 abs) is about 0.25° (0.14 K) lower than when the tank pressure builds up to 15 psia (10.3 N/cm^2 abs). However, with 20° F (11 K) of subcooling the initial fuel temperature is slightly above the saturation temperature at cruise altitude. Comparing the boiloff of fuel initially subcooled 20 F (11 K) with initially saturated fuel having a tank pressure of 15 psia (10.3 N/cm^2 abs), we find the saturated fuel has slightly lower boiloff fraction than the subcooled case. Also figure 4(b) shows the boiloff fraction is approximately doubled when the amount of subcooling is reduced from 25° to 20° F (14 to 11 K).

From boiloff comparisons such as the aforementioned one, it follows that the relative superiority of saturated fuel in tanks pressurized to a constant absolute pressure or subcooled fuel in tanks pressurized to some maximum pressure above ambient is dependent entirely upon the subcooling temperatures and pressures that can be actually obtained. Other factors will determine which approach might be most useful such as (1) difficulty and expense of fabrication of pressurized tanks (see refs. 6 and 7), (2) the ability to load fuel with adequate assured subcooling into aircraft tanks, and (3) the pressurization and pressure control problems associated with subcooled fuel (particularly the problem of adding insoluble pressurant to build up tank pressure during fuel loading and during descent to insure that tank collapsing loads do not occur).

Another possible trade-off between subcooled and saturated fuel is shown in figure 4. It will be noted that the final boiloff fraction for saturated fuel with 2.0 inches (5.08 cm) of insulation (fig. 4(a)) is almost identical to that for fuel initially subcooled 25° F (14 K) but having only 1.0 inch (2.54 cm) of insulation (fig. 4(b)). These results indicate that subcooling is a possible approach to reducing insulation volume in the aircraft.

Total insulation and boiloff weight penalties. - Figure 5 shows total weight penalties due to boiloff and insulation weight per pound of initial fuel weight in the fuselage tanks for insulation thicknesses of 0.5, 1.0, and 2.0 inches (1.27, 2.54, and 5.08 cm) applied to tanks filled with saturated methane venting at 15-psia (10.3-N/cm^2 abs) tank pressure. The figure also shows that, at an insulation thickness of 2.0 inches (5.08 cm), the boiloff weight and insulation weight are approximately equal. The minimum total weight penalty occurs when insulation weight and boiloff weight are nearly equal as concluded in reference 2 and as the calculated results show in figure 8 of reference 8. Reference 8 also shows that the optimum insulation thickness for wing tanks venting at 15-psia (10.3-N/cm^2 abs) tank pressure is 1.0 inch (2.54 cm) for the same insulation density as used in the present analysis. It can be concluded, therefore, that unless volume limitations are over-riding, it will be desirable to have thicker insulation for the fuselage tanks.

Cruise Mach number effects. - The effect of increased cruise Mach number on boiloff was obtained by comparing a Mach 2.7 mission to a Mach 3.5 mission. Cruise Mach number of 3.5 represents possible future SST missions considering the limitations and economies of future turbine engines. Figure 6 shows boiloff fraction results for the two SST missions with tanks insulated with 1.0 inch (2.54 cm) of insulation and the pressure vents set at 15 psia (10.3 N/cm^2 abs). As expected the boiloff is greater for the Mach 3.5 mission (3.1 to 2.4 percent) due to the added heat flux into the tanks which is the result of a boundary layer effective temperature of 775° F (686 K) at Mach 3.5 which is 350° F (194 K) higher than at Mach 2.7. Figure 6 also shows the coincidence of the boiloff fraction plotted against mission time graphs for both missions to cruise altitude for the first 25 minutes into the flight. For the remainder of the flight, boiloff losses are greater for the higher cruise Mach number as would be expected. As fuel is used in the engines beyond mission times of 65 and 74 minutes (for Mach 3.5 and 2.7, respectively) the rate of boiloff decreases because a steadily decreasing amount of liquid fuel is exposed to the heated surfaces of the tanks. At the end of the mission, the tanks still contain the reserve fuel, and some boiloff at a reduced rate continues. Even though there is more boiloff for the Mach 3.5 mission, the difference between the missions is only 0.007 boiloff fraction. The results of figure 6 indicate that the same insulation system (providing it can withstand the higher temperatures of Mach 3.5 flight) could be used for both Mach 2.7 and Mach 3.5 SST's with only small additional boiloff at the higher flight Mach number.

CONCLUDING REMARKS

The following conclusions can be made from the results of this analytical investigation of insulated fuselage tanks for liquid methane fueled supersonic-transport-type aircraft.

1. The cryogenic fuel, liquid methane, which boils at -260° F (111 K) at 1-atmosphere pressure can be stored in fuselage tanks with boiloff losses of less than $2\frac{1}{2}$ percent of the initial fuel weight in the tanks at a cruise flight Mach number of 2.7 using an insulation thickness of 1.0 inch (2.54 cm).

2. If the cruise flight Mach number is increased to 3.5 using the same 1.0-inch-(2.54-cm-) thick insulation system as for a flight Mach number of 2.7, the total boiloff fraction is only 3.1 percent (compared to 2.4 percent for Mach 2.7), even though the aircraft external surface temperature increases from 435° to 775° F (497 to 686 K).

3. Similar fuel boiloff losses are encountered either by using tanks that can withstand a vent pressure of 15 psia (10.3 N/cm^2 abs) and loading the tanks with saturated methane, or by using tanks that can withstand an internal pressure of only 4 psi (2.8 N/cm^2) above ambient pressure, and loading the tanks with fuel initially subcooled slightly more than 20° F (11 K). The amount of initial subcooling has a very significant effect on boiloff losses. Reducing the initial subcooling from 25° to 20° F (14 to 11 K) approximately doubles the boiloff from the fuselage tanks.

4. If the optimum insulation thickness is defined as the thickness that results in minimum total weight penalty for insulation weight plus boiloff weight, the optimum thickness is approximately twice that for fuselage tanks (2.0 in. or 5.08 cm) as it is for wing tanks (1.0 in. or 2.54 cm) for tank vent pressures of 15 psia (10.3 N/cm^2 abs) and the methane loaded in the saturated state.

5. The percentage of fuel boiled off during loading is somewhat lower for fuselage tanks than for wing tanks because of a more favorable tank volume to wetted area ratio. For a 21-minute fill time for the tanks, the maximum boiloff rate is approximately one twenty-fifth of the fill rate and the average boiloff rate is less than one-seventieth of the fill rate.

6. Fuselage tank fuel boiloff can be essentially eliminated with insulation thicknesses as low as 0.5 inch (1.27 cm) if the fuel is loaded in a saturated state at 1-atmosphere vapor pressure and the tank can withstand a vent pressure of 30 psia (20.7 N/cm^2 abs).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 2, 1970,
720-03.

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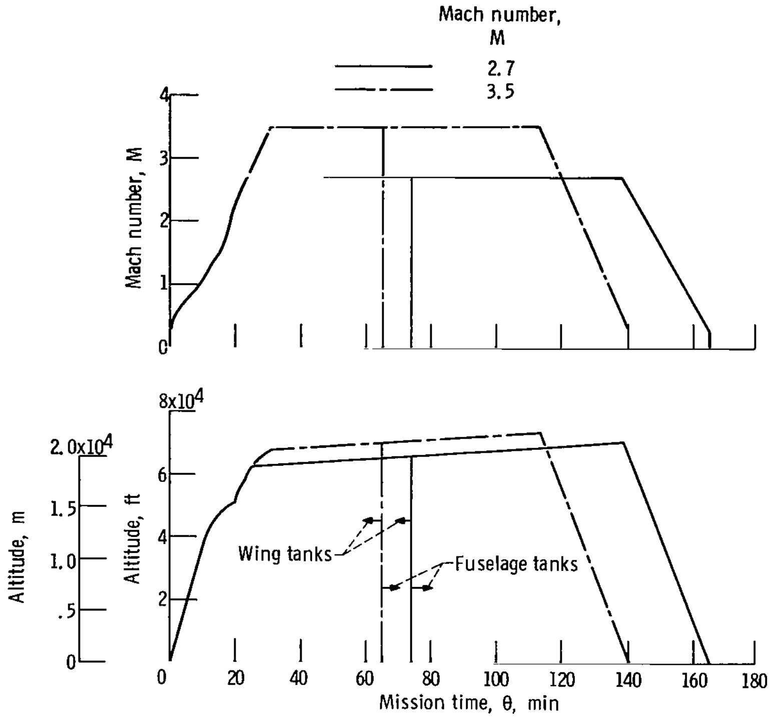
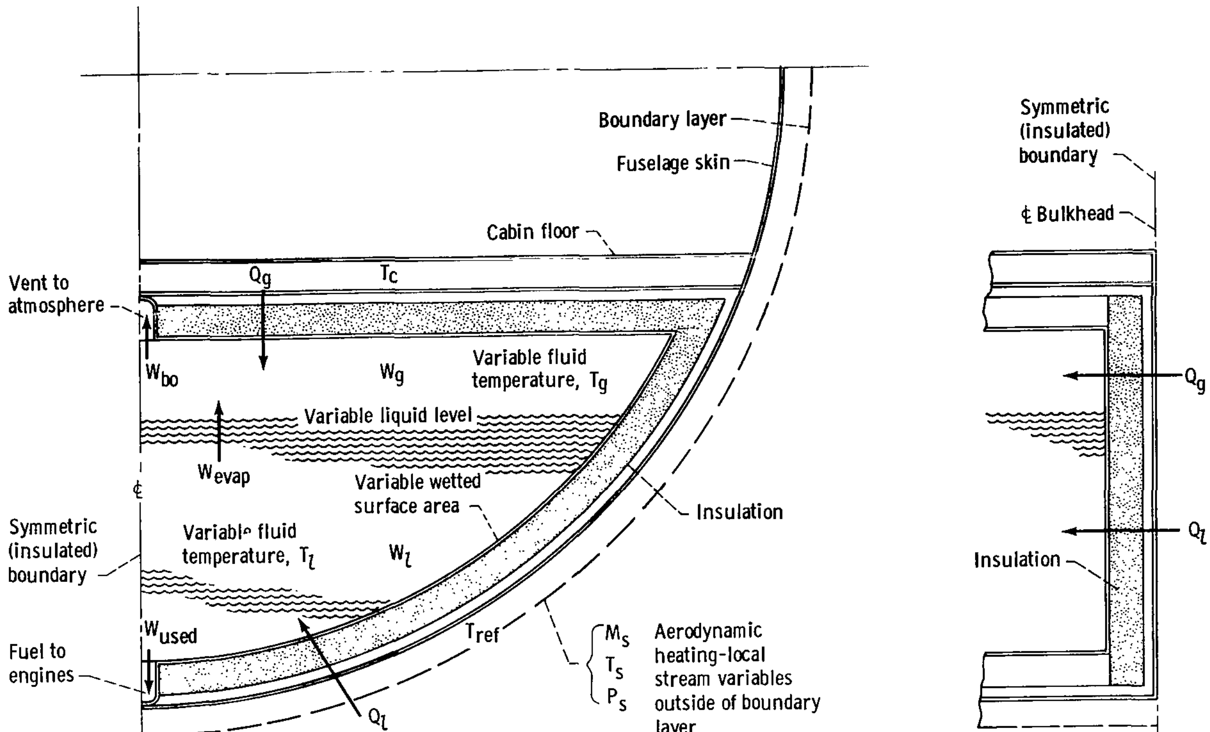


Figure 1. - Flight plans for missions at cruise Mach numbers of 2.7 and 3.5.



(a) Basic tank section.

(b) Tank end.

Figure 2. - Heat transfer model.

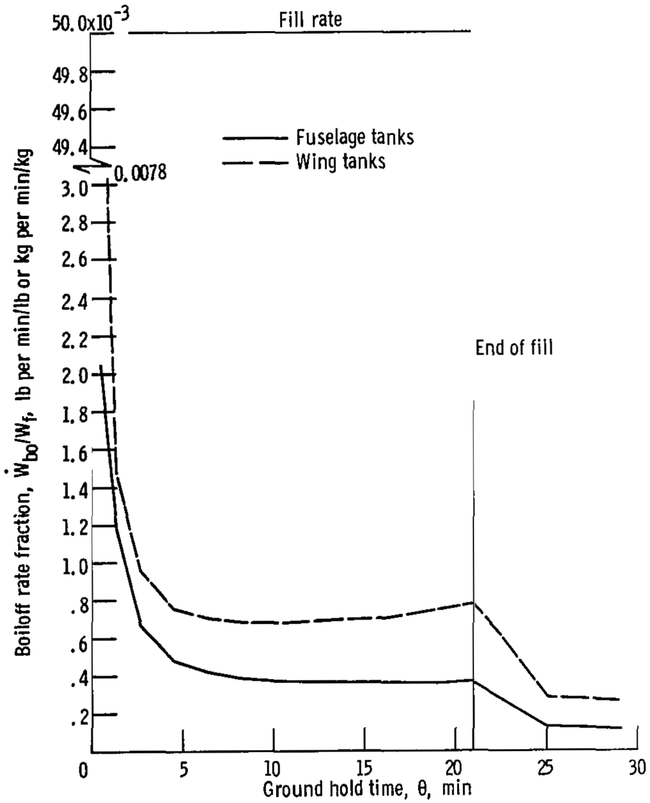
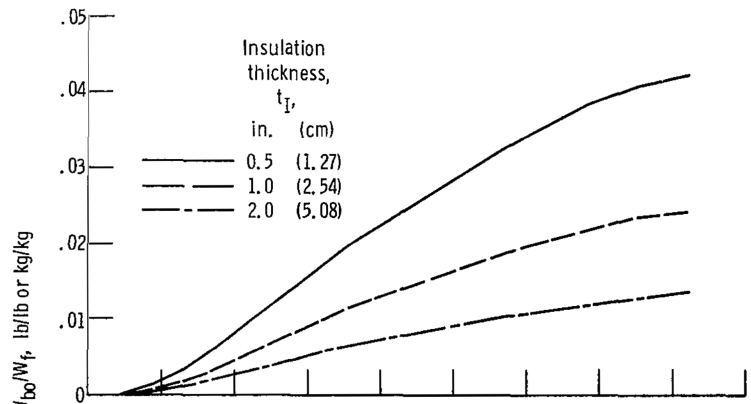
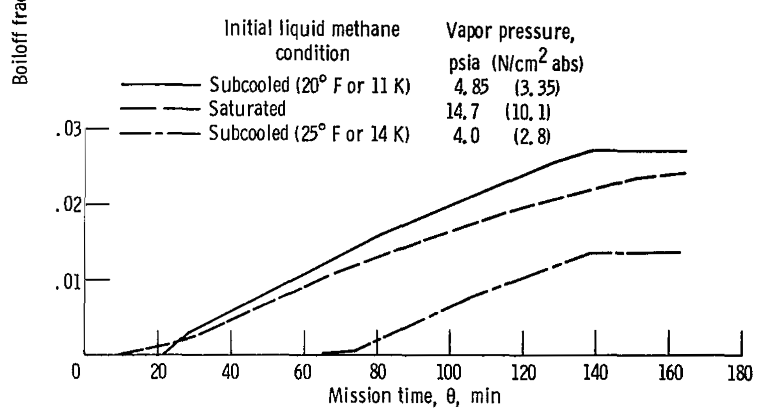


Figure 3. - Boiloff rate fraction during tank fill and ground hold for fuselage and wing tanks. Insulation thickness, 1.0 inch (2.54 cm); specific weight, 2 pounds per cubic foot (32 kg/m^3); saturated liquid methane at 14.7-psia (10.1-N/cm^2 abs) vapor pressure.



(a) Effect of insulation thickness. Tank vent pressure, 15 psia (10.3 N/cm^2 abs); saturated liquid methane at 14.7-psia (10.1-N/cm^2 abs) vapor pressure.



(b) Effect of initial fuel condition. Insulation thickness, 1.0 inch (2.54 cm); subcooled methane vented at 4 psi (2.8 N/cm^2) above ambient; saturated methane at 15-psia (10.3-N/cm^2 abs) vent pressure.

Figure 4. - Fuel weight fraction of methane boiloff during Mach 2.7 mission.

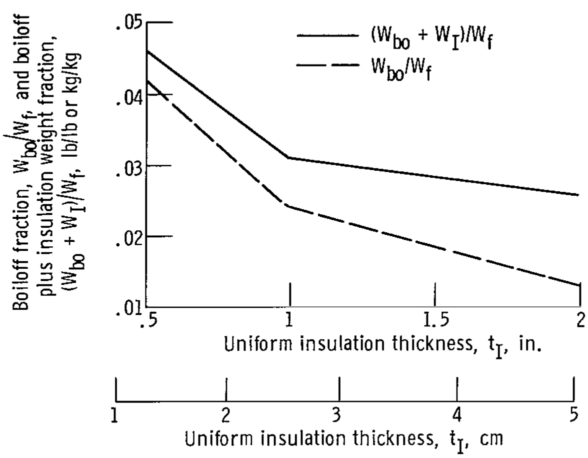


Figure 5. - Fuel weight fraction of insulation weight and methane boiloff for fuselage tanks with various insulation thicknesses. Specific weight, 2 pounds per cubic foot (32 kg/m^3); tank vent pressure, 15 psia (10.3 N/cm^2 abs); saturated liquid methane at 14.7-psia (10.1-N/cm^2 abs) vapor pressure.

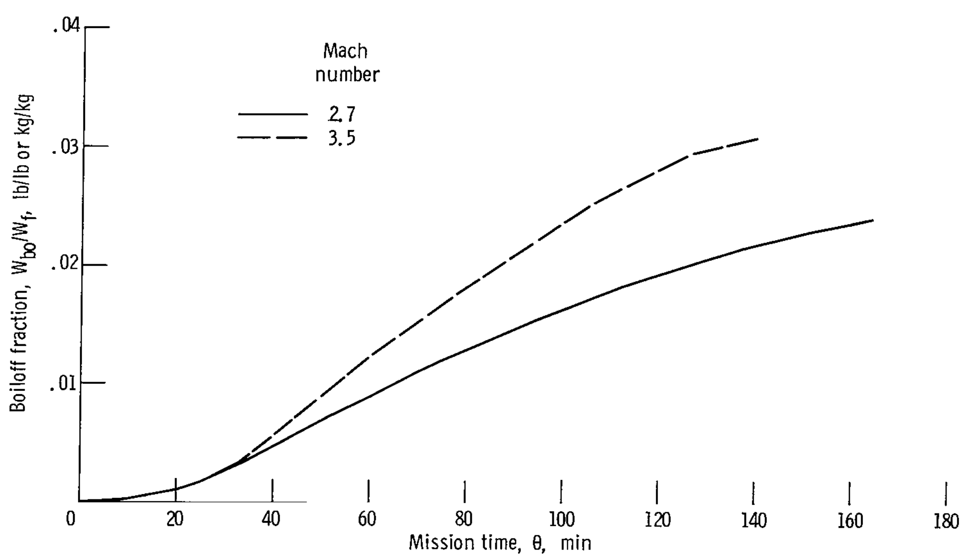


Figure 6. - Effect of increased cruise Mach number on fuel weight fraction of methane boiloff. Insulation thickness, 1.0 inch (2.54 cm); tank vent pressure, 15 psia (10.3 N/cm^2 abs); saturated liquid methane at 14.7-psia (10.1-N/cm^2 abs) vapor pressure.

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